Coronal Mass Ejections in the Heliosphere

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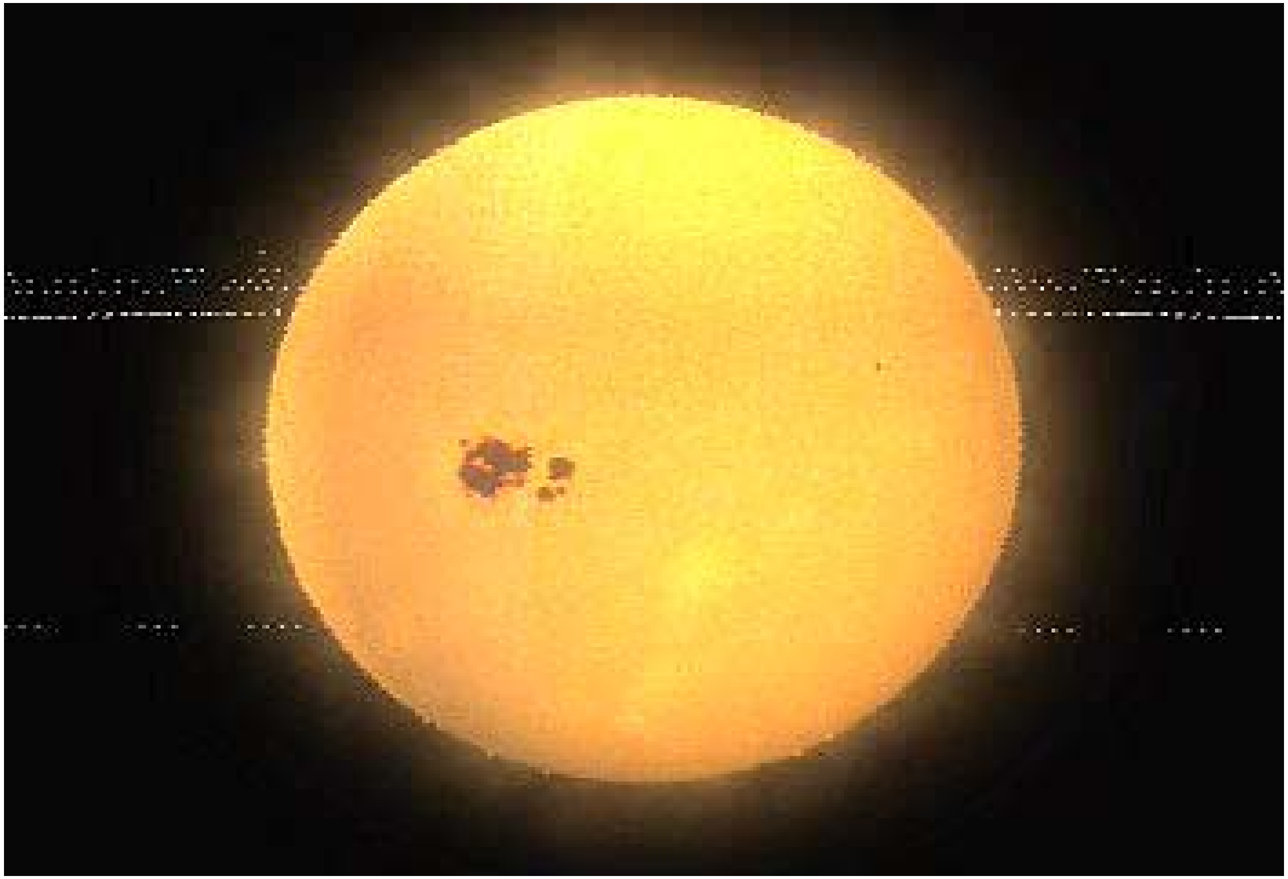
http://cdaw.gsfc.nasa.gov/publications

Plan

- General Properties
- Rate & Solar Cycle Variability
- Relation to Polarity Reversal
- CMEs and Cosmic ray modulation
- SEPs radio bursts
- CMEs and Geomagnetic storms
- Summary

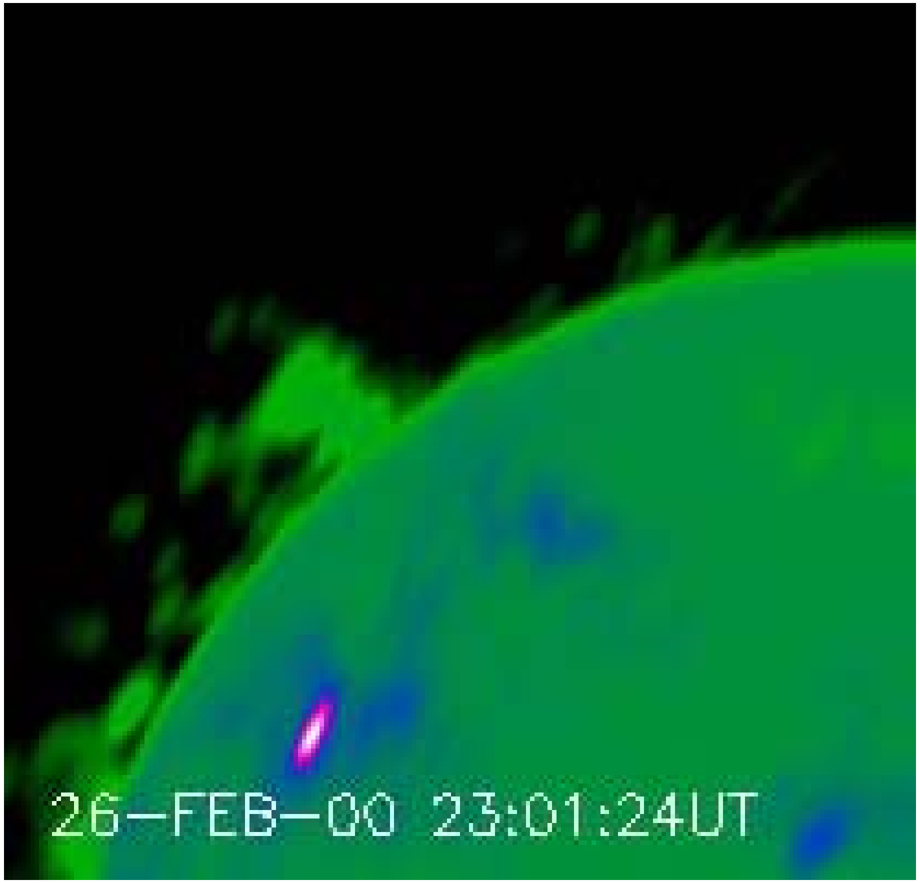
Animation of Halloween 2003 Events



… to illustrate their heliospheric impact

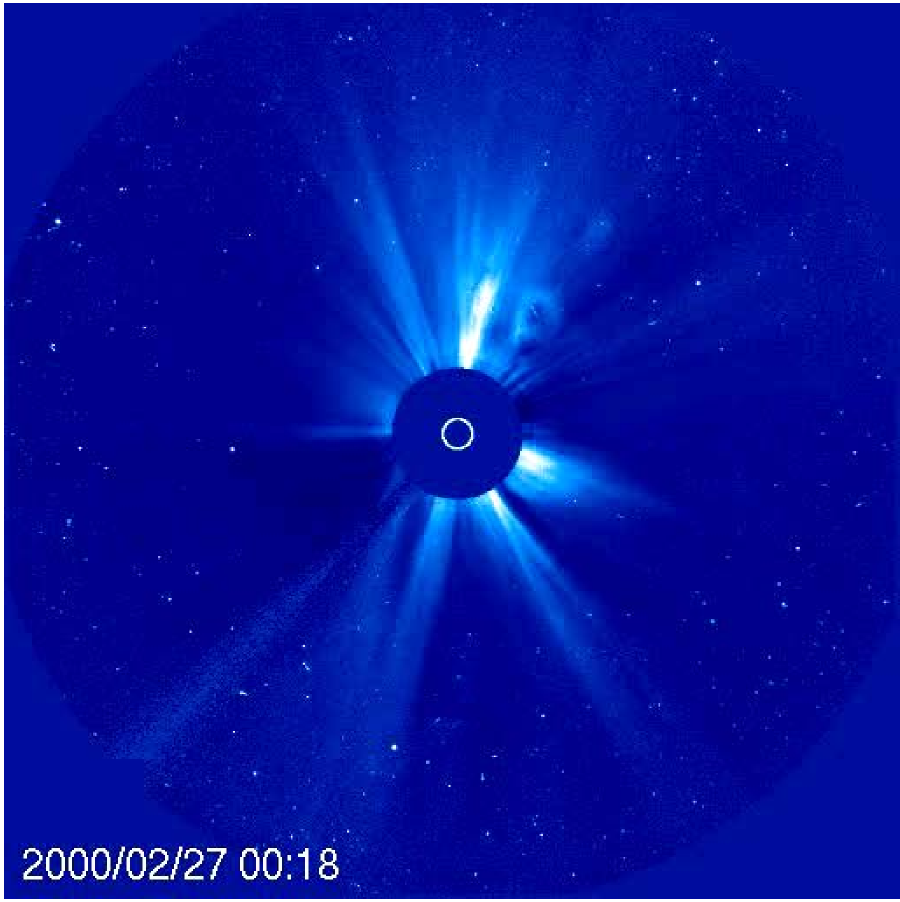
What is a CME?

A prominence eruption that becomes CME core (in microwaves, Nobeyama)

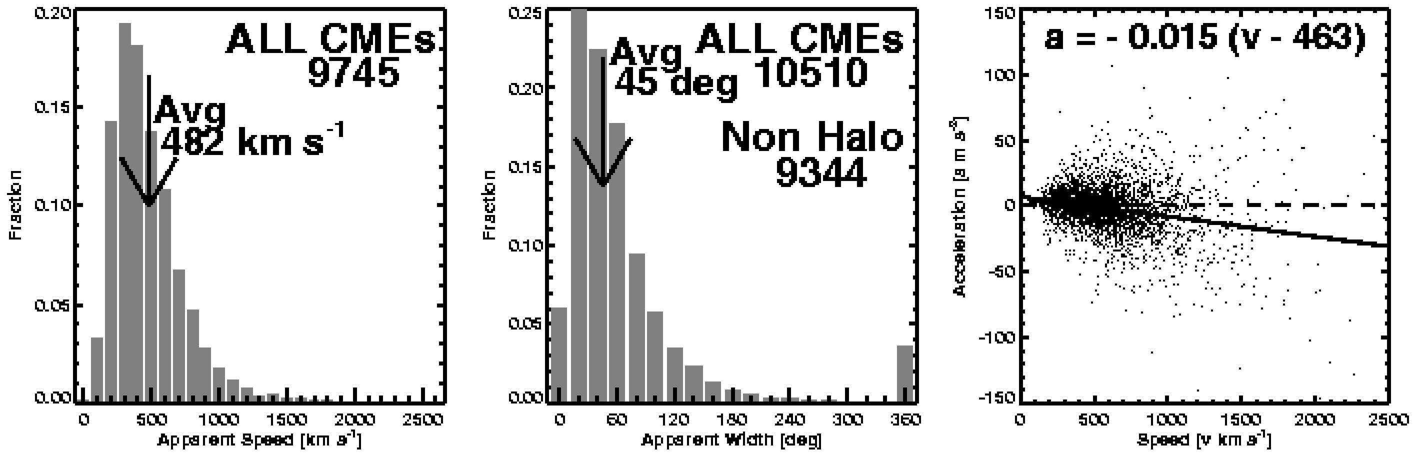


Brightening on the disk is the associated flare

SOHO/LASCO sees the CME Later in the corona with the core



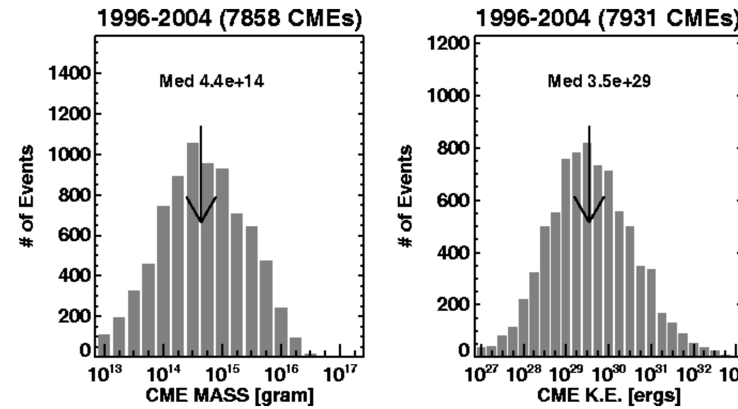
Statistical Properties



CME acceleration *a* depends on speed

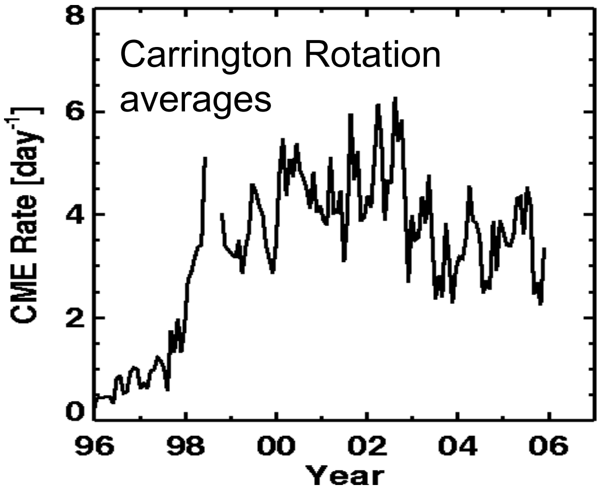
a = 0 when *v* = 463, a crude estimate of solar wind speed

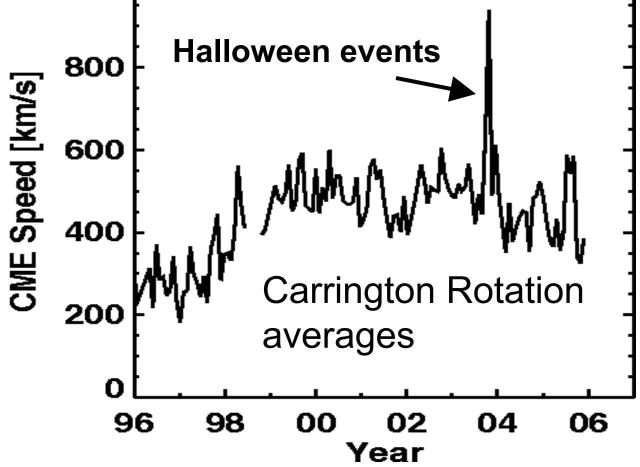
- The number of SOHO CMEs is an order of magnitude higher than that of pre-SOHO CMEs
- The average speed and width (of non-halo CMEs) are similar to pre-SOHO values
- The highest speed observed increased significantly to 3347 km/s, but the fraction of CMEs with V > 2500 km/s is tiny (10^{-4})
- The number of halo CMEs is significantly larger (~3%)
- Statistically, faster CMEs decelerate
- The average mass of SOHO CMEs is smaller than pre-SOHO values (due to SOHO's better dynamic range)

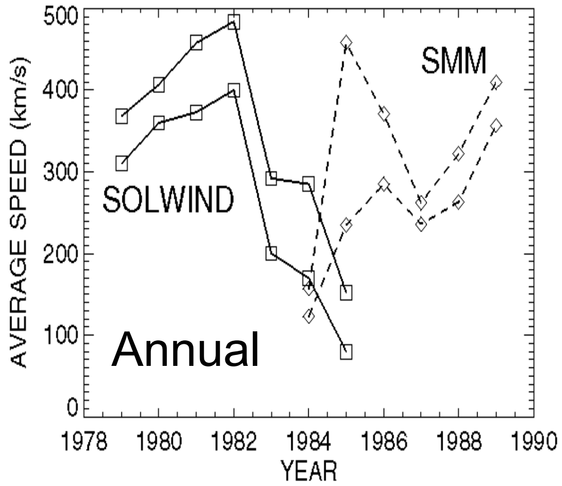


SOHO observed more low-mass CMEs resulting in a smaller average mass

Solar Cycle Variation of CME Rate and Speed



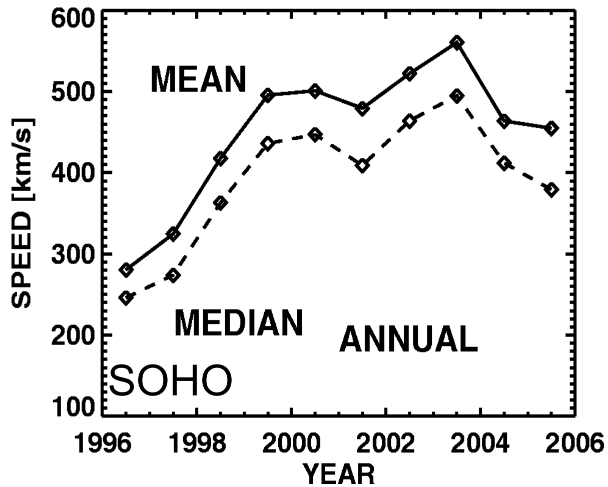




SOHO CME rate increased from ~0.5/day during solar minimum to ~6/day during maximum. The maximum rate is higher by a factor of 2 (pre-SOHO max rate ~3/day)

The pre-SOHO correlation between sunspot number and CME rate was confirmed, but the correlation was weaker. This seems to be due to the high-latitude CMEs that started in 1999 from polar crown filament region

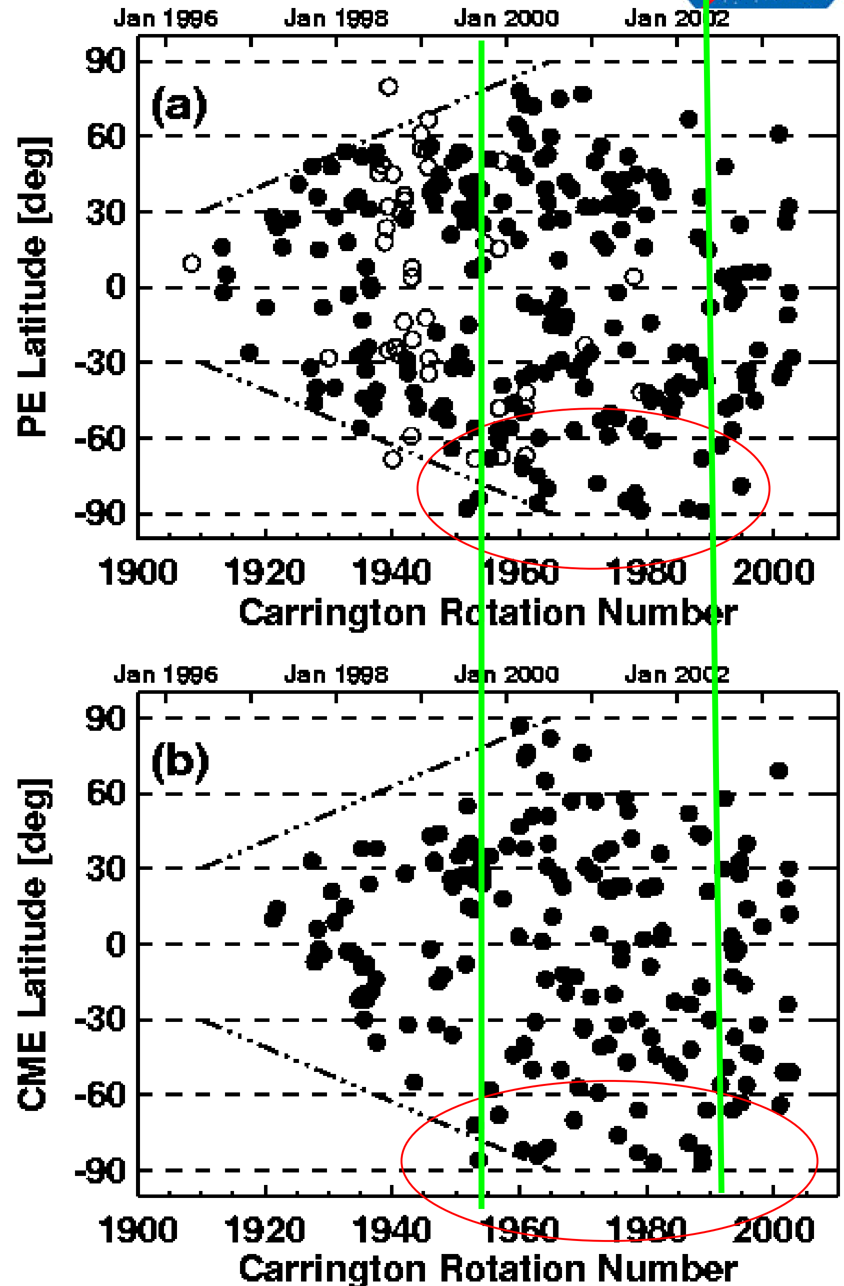
The solar cycle variation of average CME speed was inconclusive in the pre-SOHO era. SOHO data confirmed the increase from minimum to maximum by a factor of 2. The spikes in the speeds are due to some active regions, which are copious producers of fast CMEs.



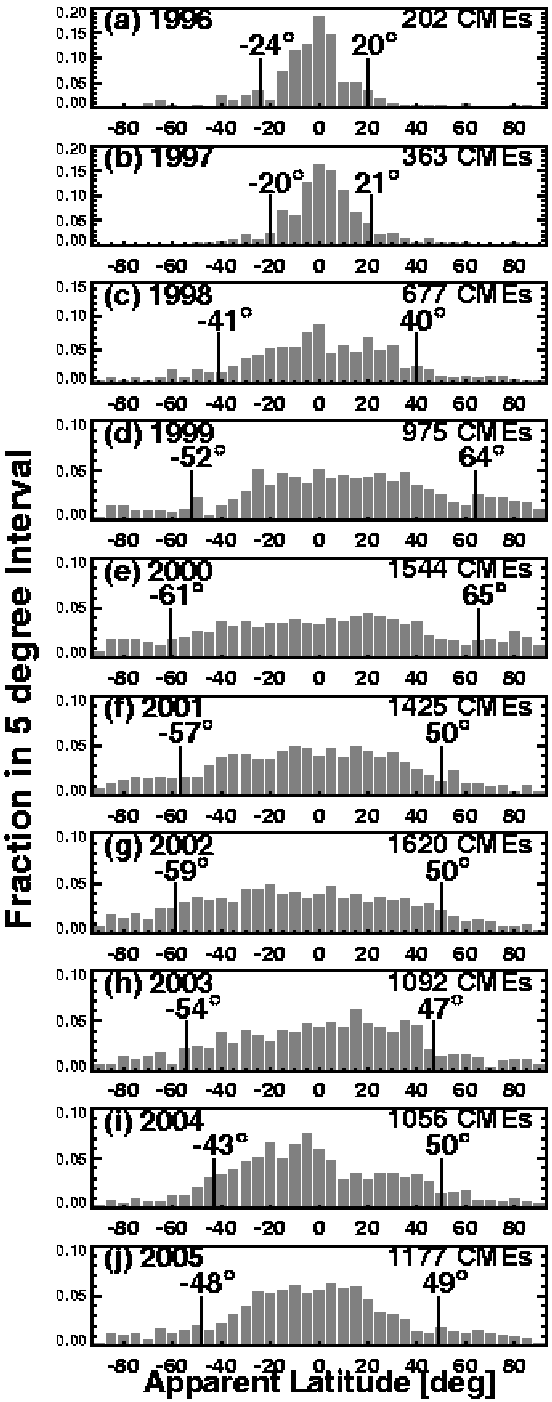
CMEs & Prominences

- High latitude prominence eruptions and CMEs during CR 1950-1990 (mid '99 – early '02)
- N-S asymmetry
- These CMEs are not associated with sunspot activity

- hence the poor correlation between CME rate & SSN

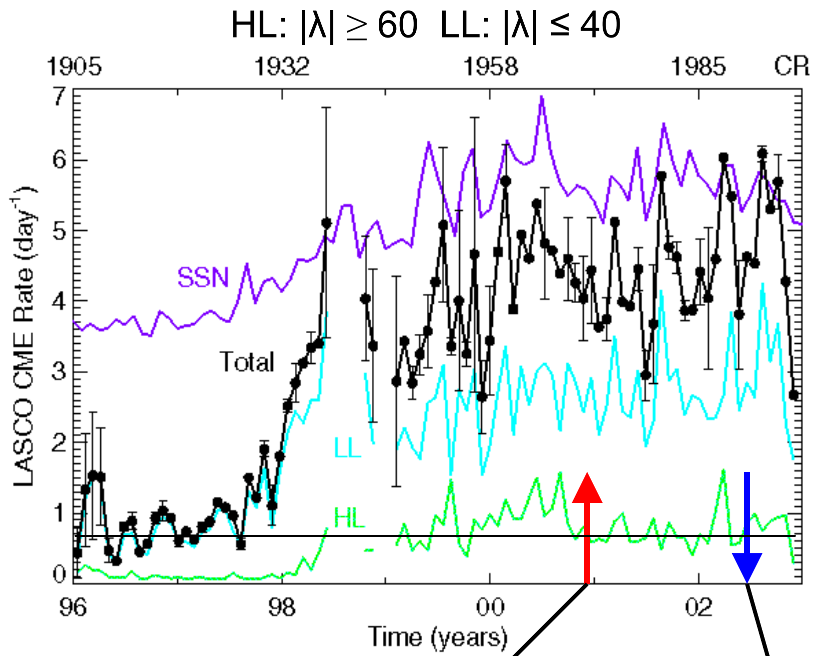


High & Low latitude CMEs



The average latitude changes significantly over the solar cycle

2005 distribution looks similar to that in 1998



Polarity reversal in the northern hemisphere

Polarity reversal in the southern hemisphere

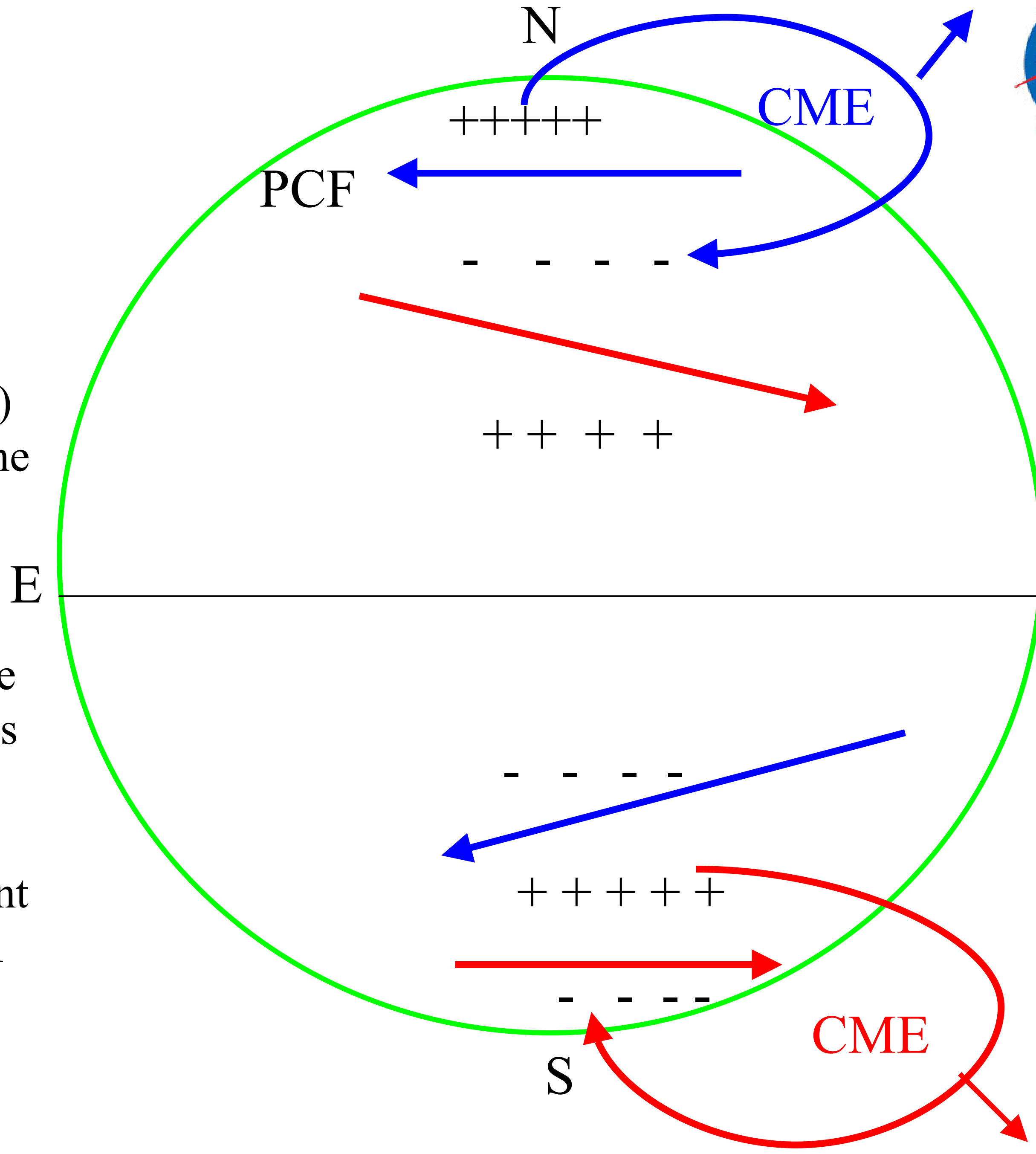
Polarity reversal coincides with the cessation of HL CMEs separately in the northern and southern hemispheres

Solar magnetic filed pattern before reversal

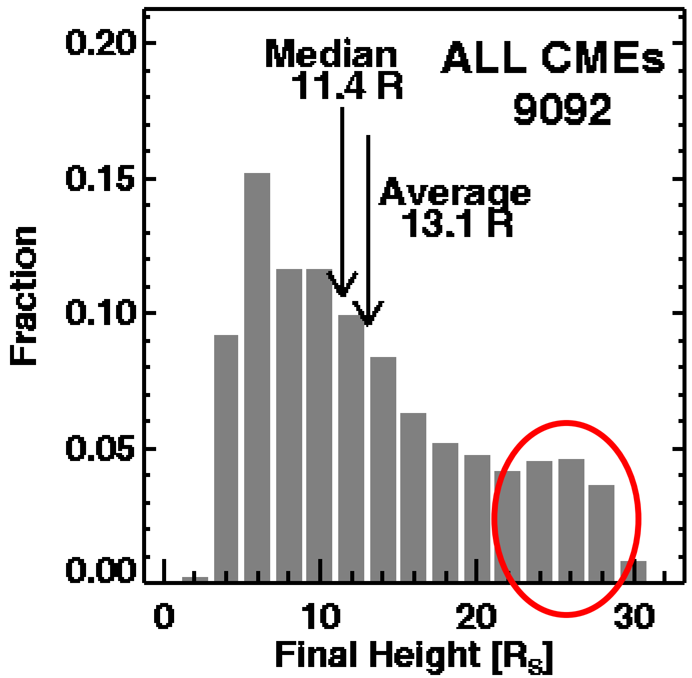
The blue structures (Magnetic field in the polar crown filaments) must be replaced by the red for reversal in the north.

This happens when the high-latitude structures disappear as CMEs

The red fields represent the future polar crown filament in the north



CMEs Affecting the Heliosphere

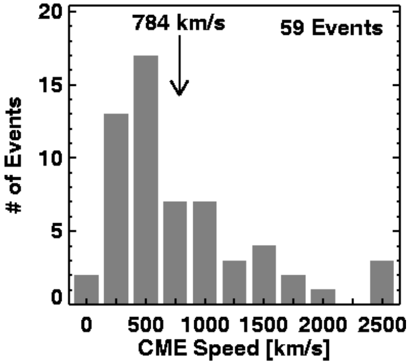


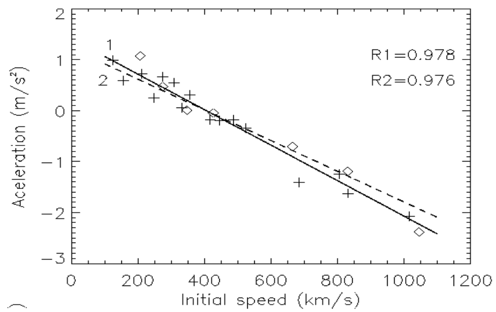
July 10 2000 – February 5, 2001 (7 months); Ulysses poleward of S60 courtesy: J. T. Gosling

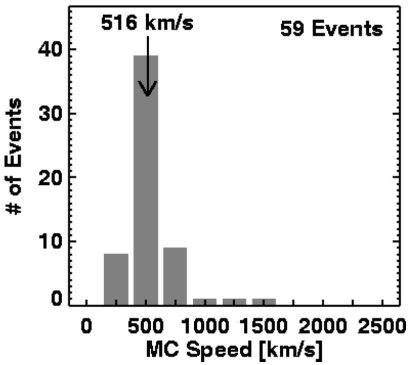
Ulysses	LASCO HL	LASCO LL	1 AU
8	101	602	25
8%			4% (8% excluding Backsided CMEs)

~ 10% of CMEs leaving the Sun seem to reach far into the heliosphere
Consistent with the 11% wide CMEs; Similar fraction reaches the edge of the LASCO FOV

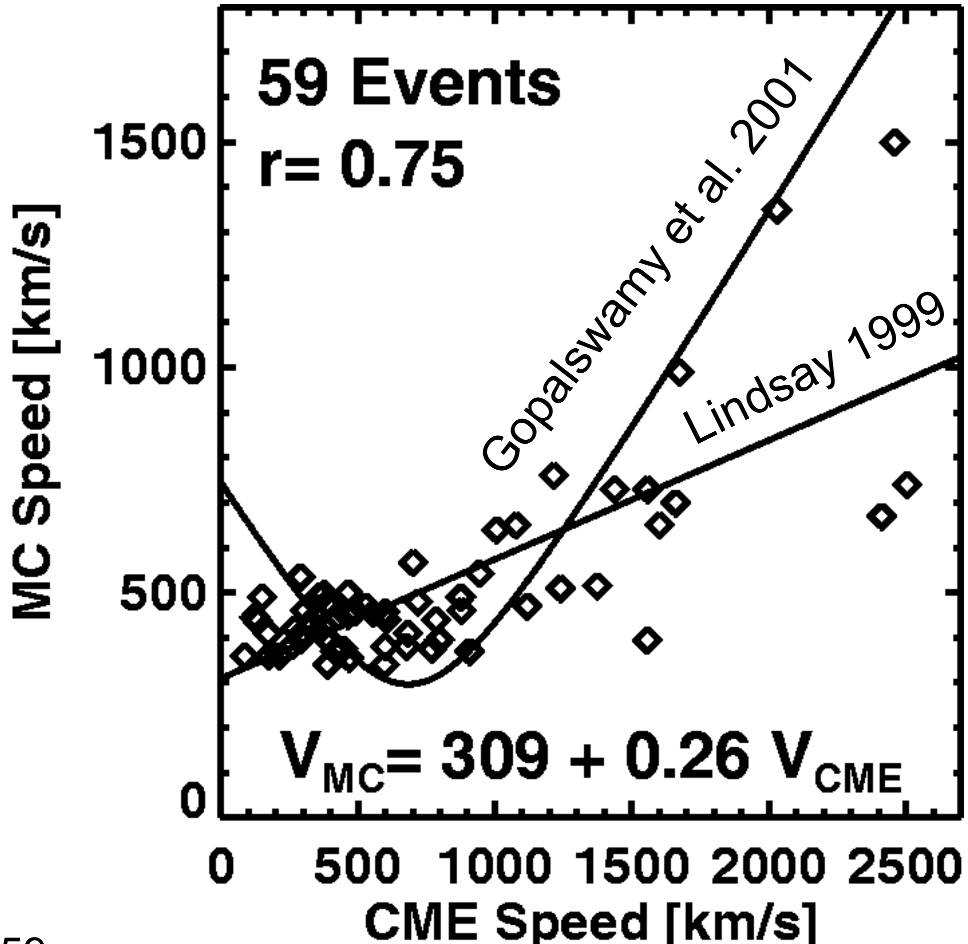
CME-ICME Relationship







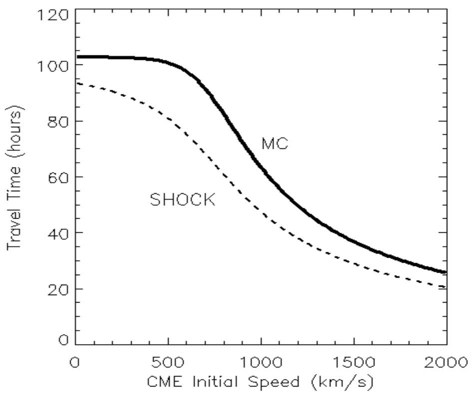
a = - 0.0054V + 2.193
a = - 0.0054 (V – 406)
a =0 for V=406 → CMEs riding on the solar wind



The speed distribution of CMEs and ICMEs for 59 pairs (from Gopalswamy et al. 2000 GRL).

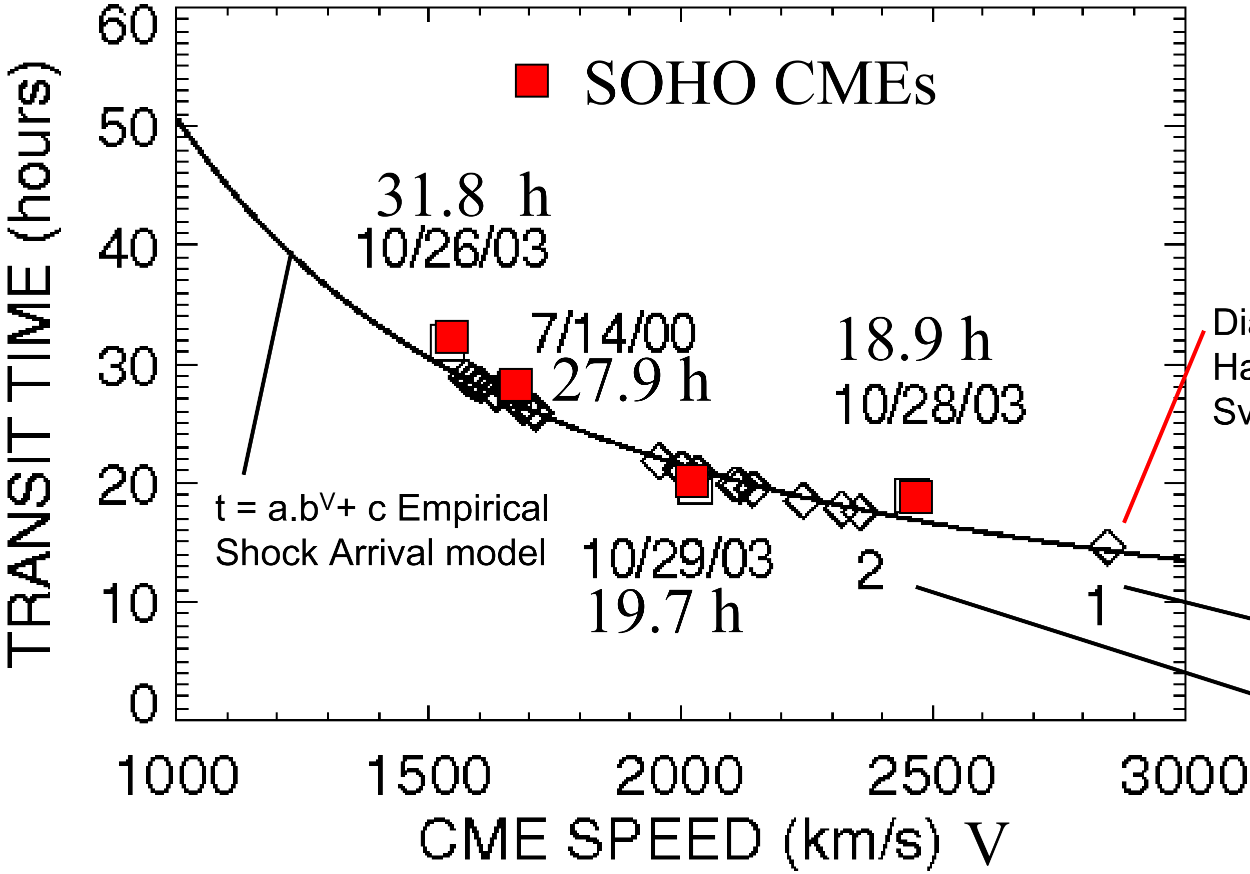
Transit Time of Shocks & CMEs

The IP acceleration can be used to estimate the CME transit time to Earth. The shock transit time can be obtained from the CME transit time by estimating the standoff distance.



Empirical models for shock and CME arrival at Earth

SOHO contributed 2 events to the historical fast transit events compared with a simplified formula for the shock transit time.



Diamonds: historical flare-SSC time from Hale 1931, Newton, 1943, Cliver & Svalgaard 2004, Gopalswamy et al 2005

Aug 4, 1972

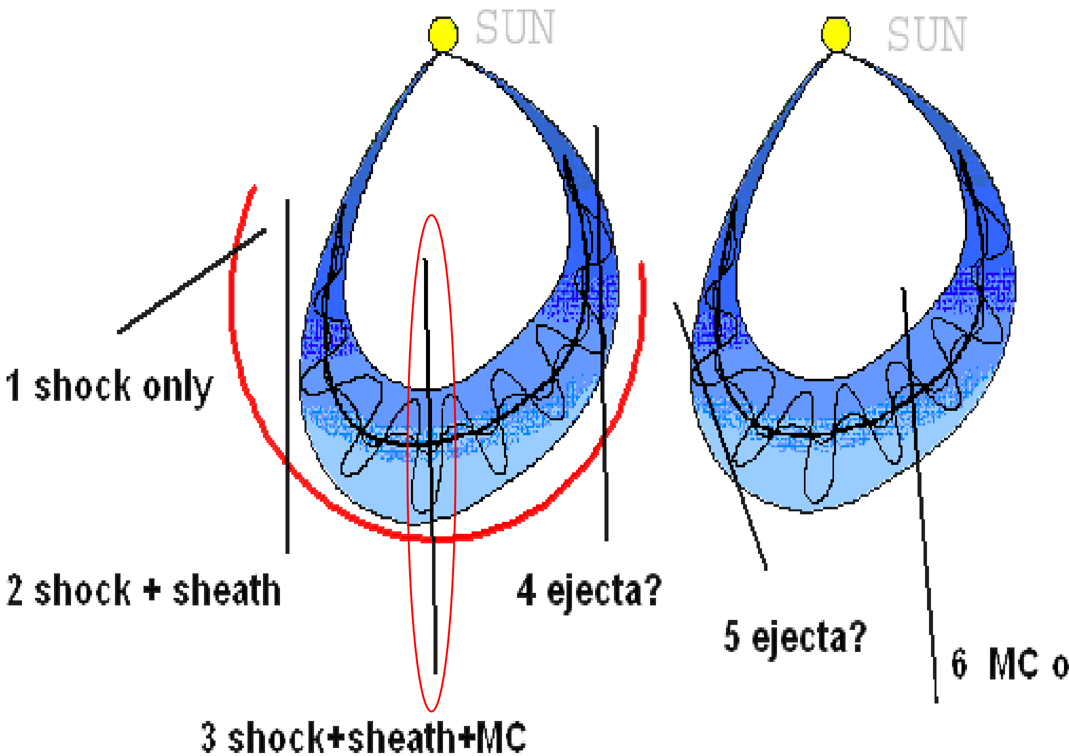
Sep 1, 1859 Carrington

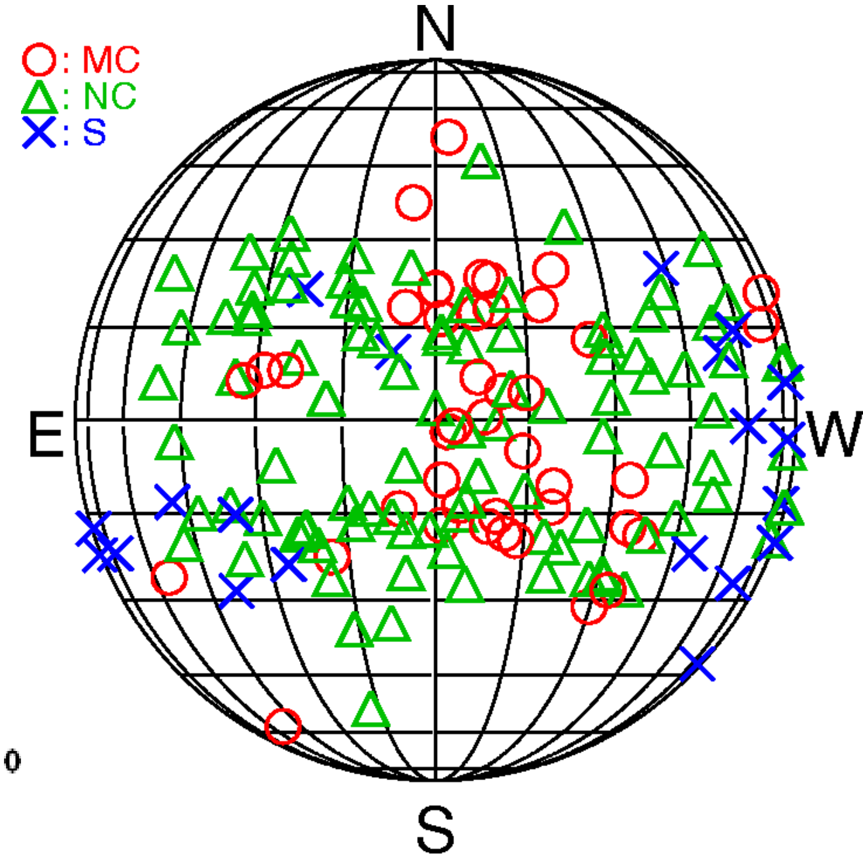
From Gopalswamy et al. 2005 JGR

Relative Number of MCs and ICMEs

Magnetic clouds (MCs) generally originate from close to the disk center,
Non-cloud ICMEs (NC) have a large scatter in source locations.
shocks (S) without drivers are due CMEs originating from close to the limb.

Non-cloud: deviation from 3





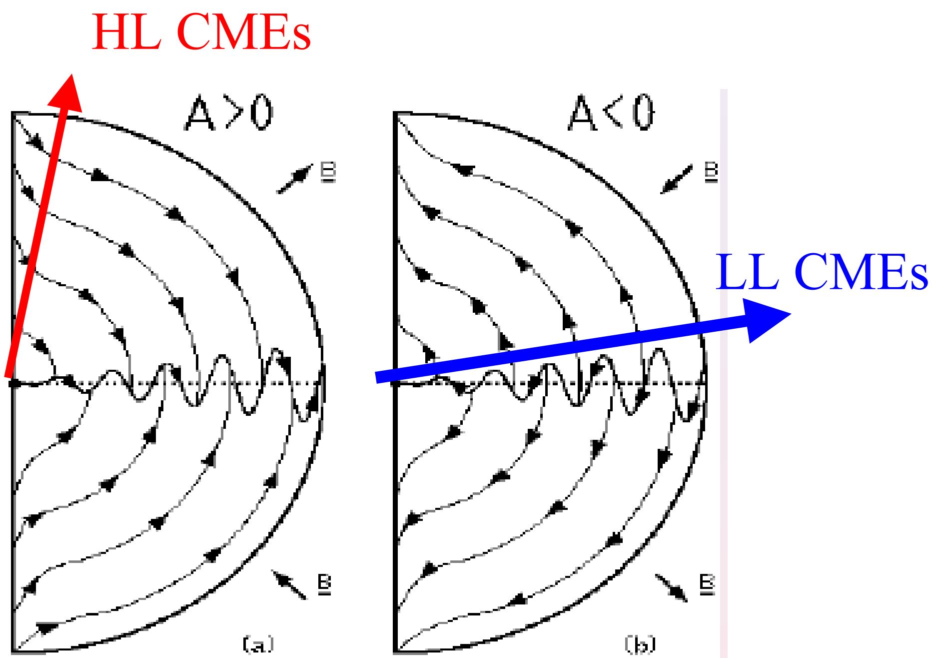
CMEs and GCR Modulation

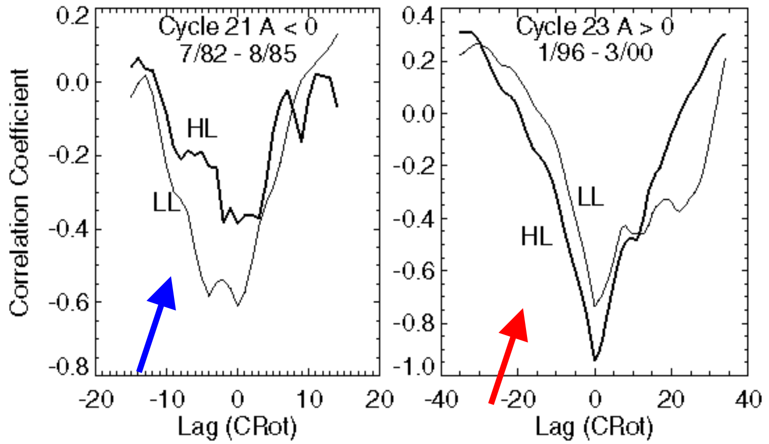
Newkirk, Hundhausen, Pizzo, 1981

CMEs play a role in the modulation of galactic cosmic rays (GCRs). Solar cycle dependent cosmic ray modulation can be explained by the presence of CME-related magnetic inhomogeneities in the heliosphere.

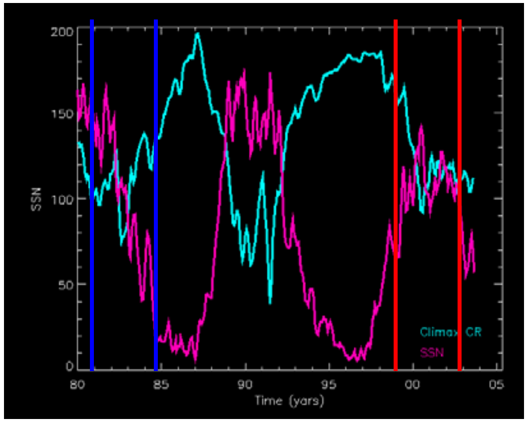
Pre-SOHO:
Rate was not high enough
Min to max variation was too low

CMEs and GCR Modulation





CME rate high enough
Min to max variation high enough
Contribution from High-latitude CMEs



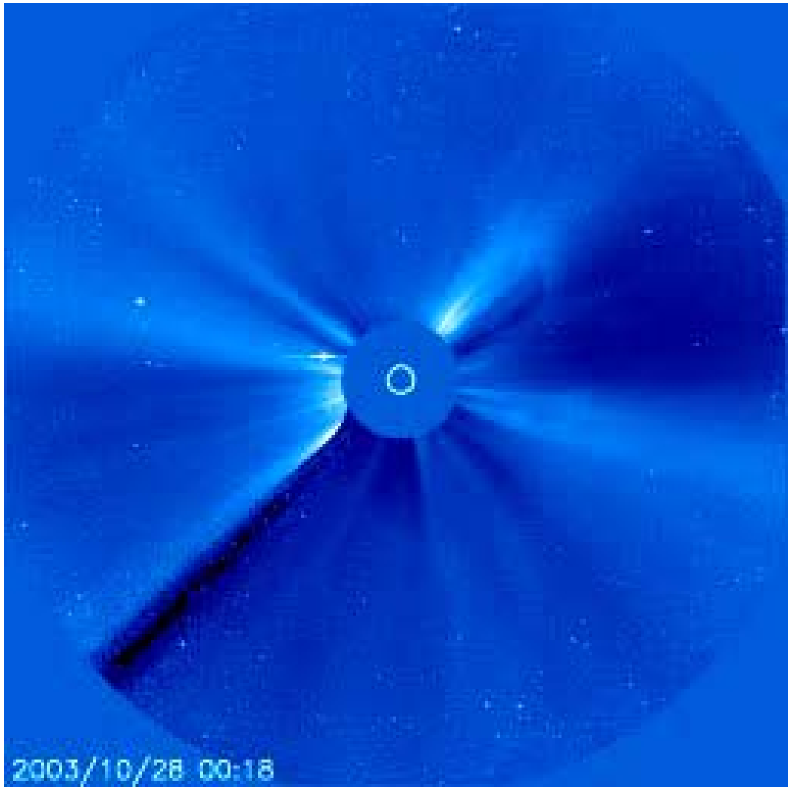
Impact of Plasmas & Particles

A CME headed Earthwards
SEPs acceleration starts when the CME is close to the Sun (a few Rs)

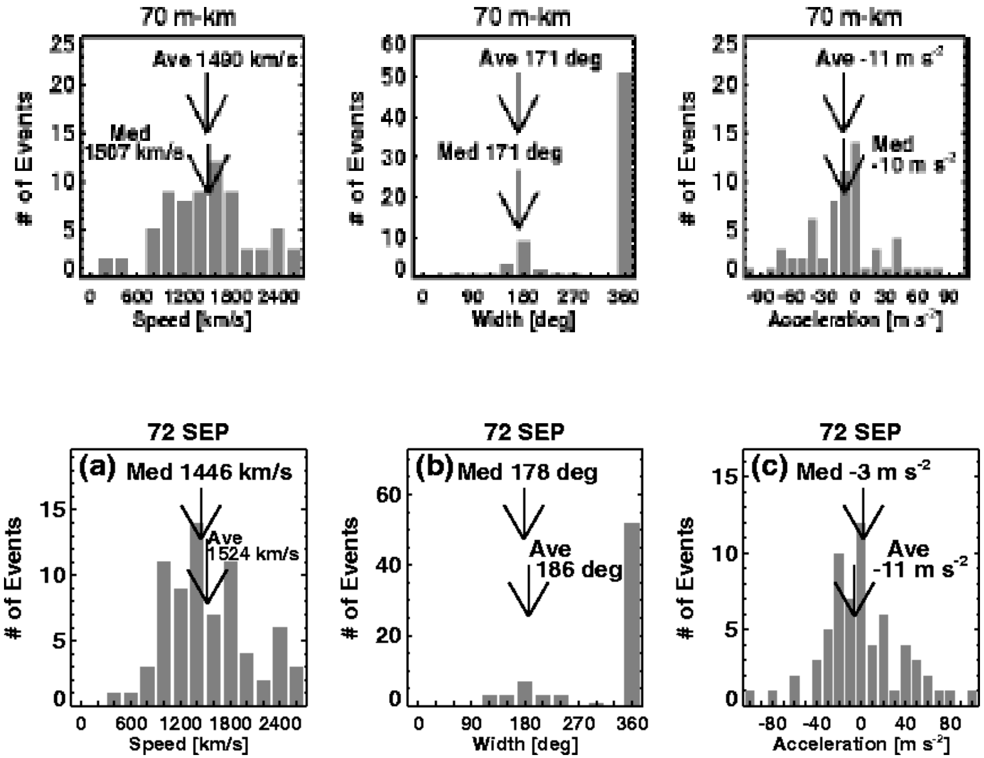
SEPs reach SOHO (located along the SUN-Earth line at L1) in 10s of minutes

SOHO detectors blinded by SEPs

SOHO's performance in imaging the corona is temporarily affected
--Sometimes fatal

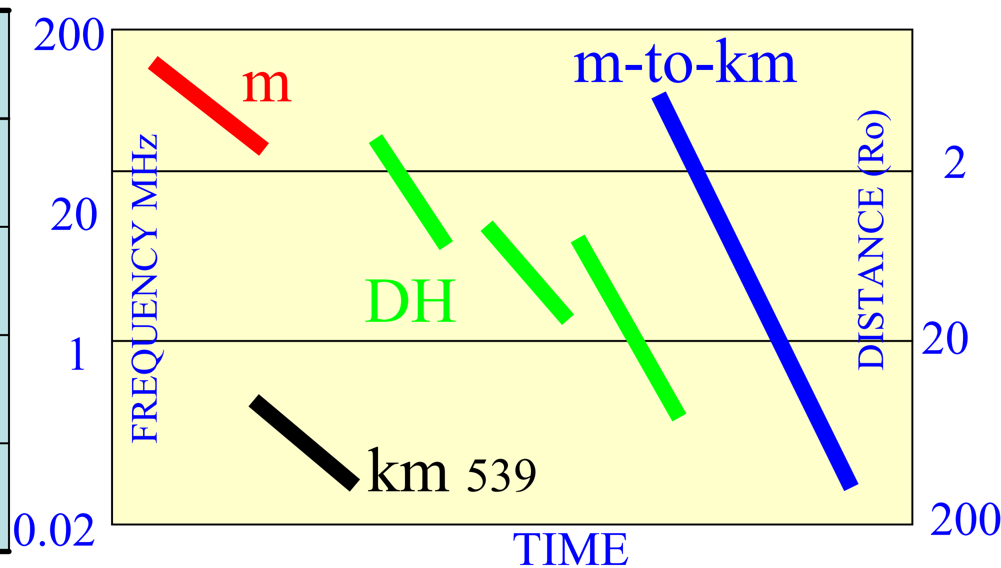


CME-Type II Hierarchy

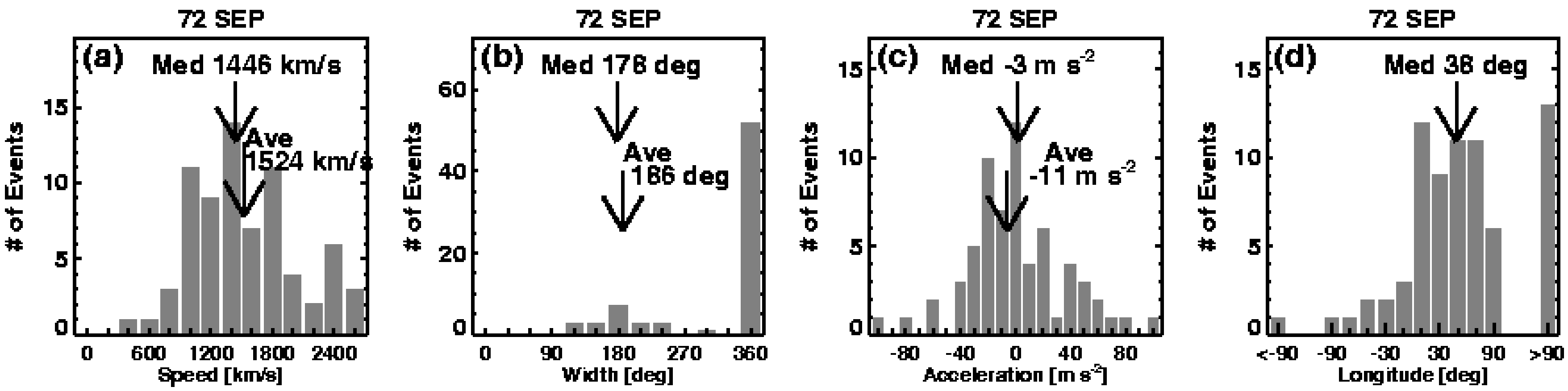


- The CME kinetic energy (speed, width) decides the wavelength range of type II bursts.
- Speed, width, & deceleration progressively increase for CMEs associated with metric, Decameter-hectometric (dh) and metric to kilometric (m-to-km) Type II bursts
- km type IIs have positive acceleration → shock formation at large distances from the Sun
- CMEs with m-to-km type II bursts are also associated with SEP events (same shock accelerates electrons & protons)

CME Property	All	m	DH	mkm SEP	km
Speed (km/s)	487	610	1115	1490 1524	539
Width (deg)	45	96	139	171 186	80
Halos (%)	3.3	3.8	45.2	71.4 72	17.2
Accel. (m/s^2)	-2	-3	-7	-11 -11	+3

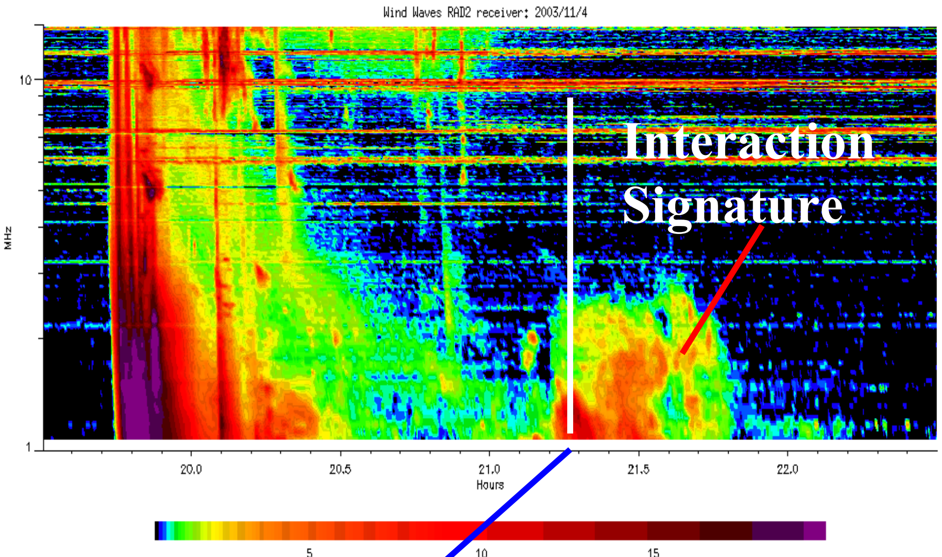


SEP Associated CMEs



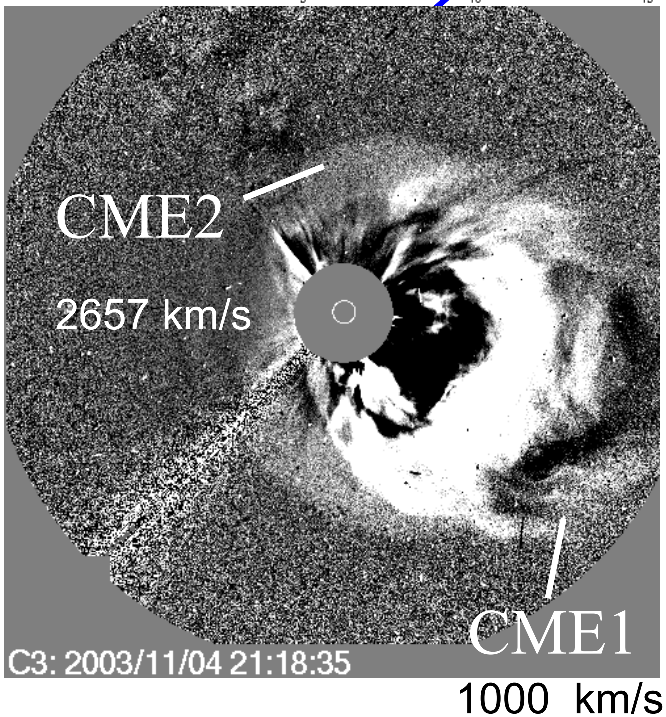
- CMEs have very high speed (Avg ~ 1500 km/s) compared to 480 km/s
- Most CMEs are halos (72%); non-halos are wide (avg ~186 deg) : 45 deg
- Most CMEs decelerating (sign of high speed) – drag: ~0 m/s^2
- Generally western source (Avg ~38 deg); many behind west limb (18%)

CME Interaction



Interacting CMEs results in enhanced radio emission in the IP medium → additional electrons accelerated (Gopalswamy et al., 2001ApJL)

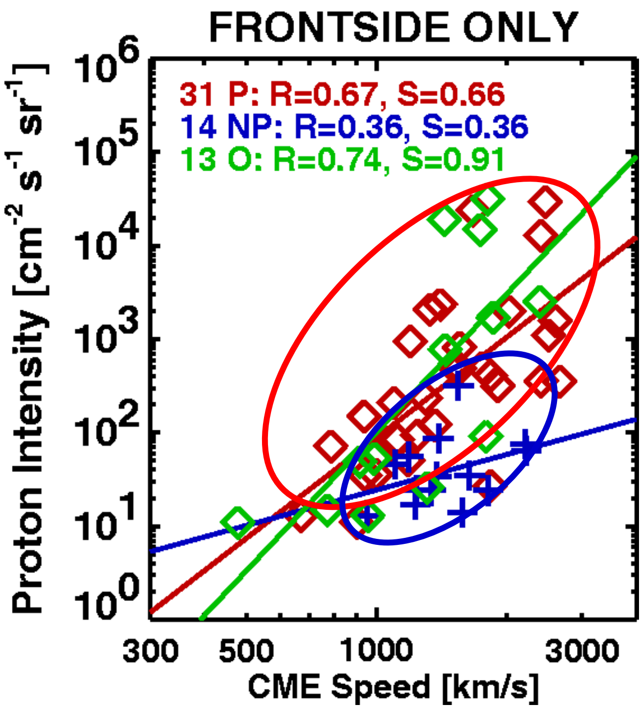
SEP-related CMEs seem to be launched into a medium distorted and disturbed by preceding CMEs.



CMEs with preceding CMEs (P,O) from the same AR result in higher SEP intensity compared to those without (NP).

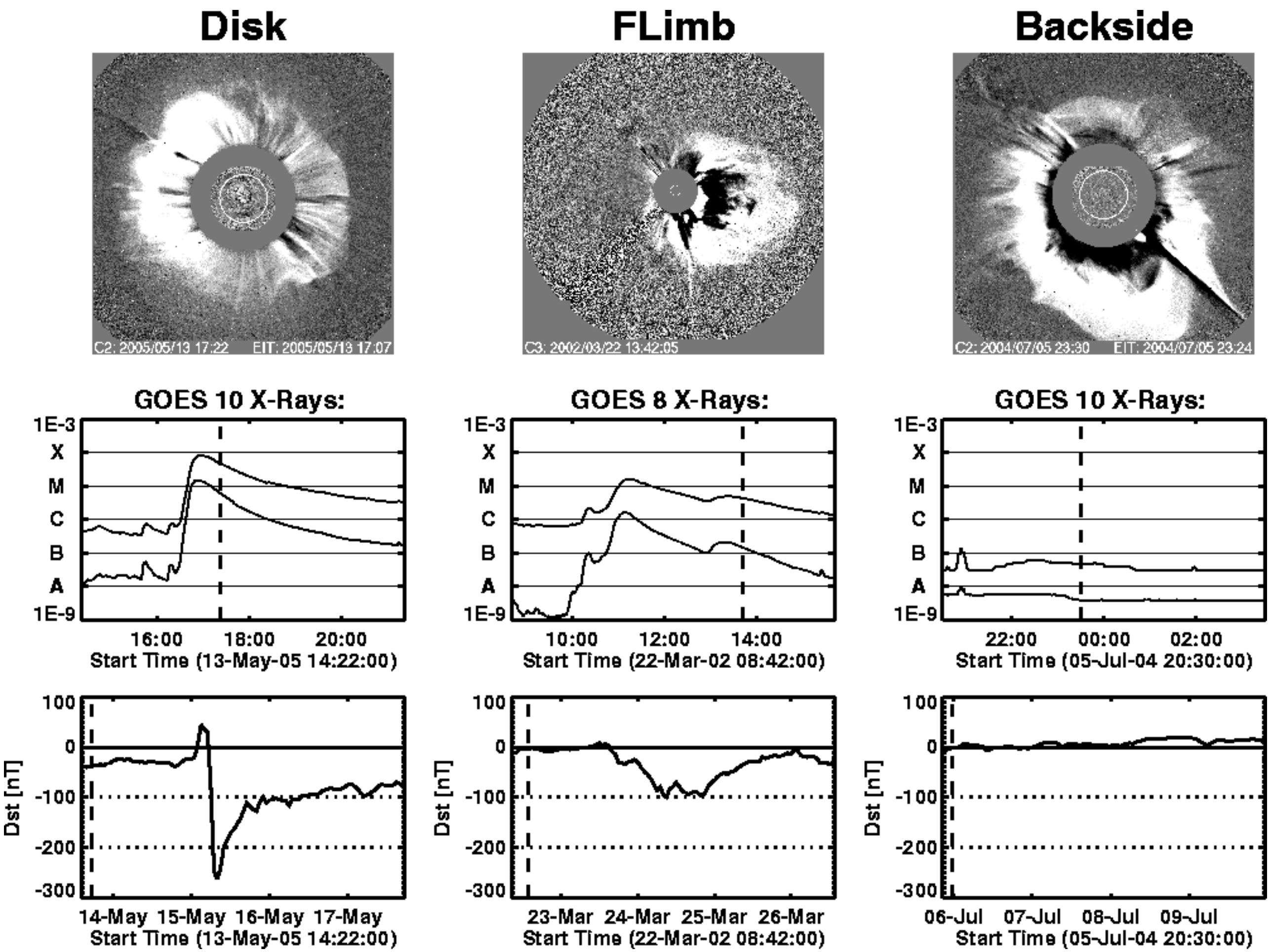
The scatter in the SEP intensity vs. CME speed plot is also reduced when P and NP events are separated

High intensity SEP events are 3 times more likely to be preceded by wide CMEs within a day

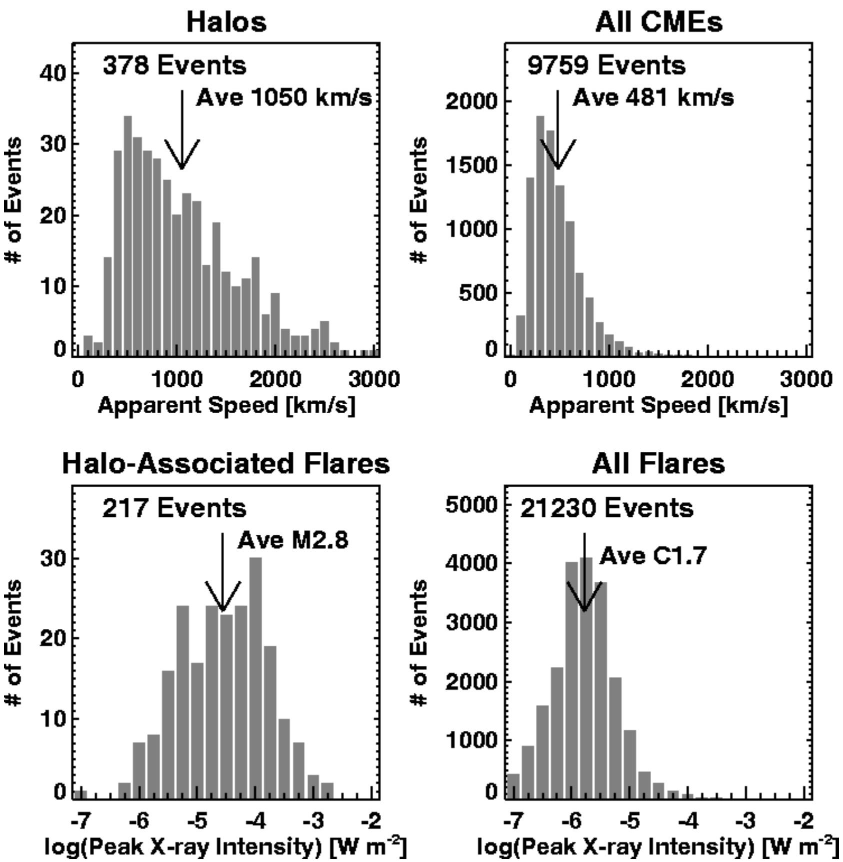


Gopalswamy et al. 2004 JGR

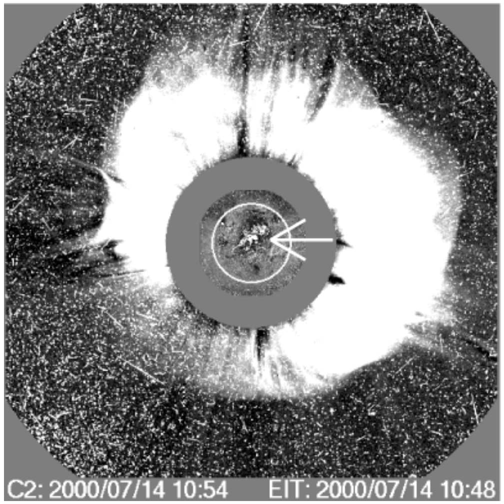
CMEs and Geomagnetic storms



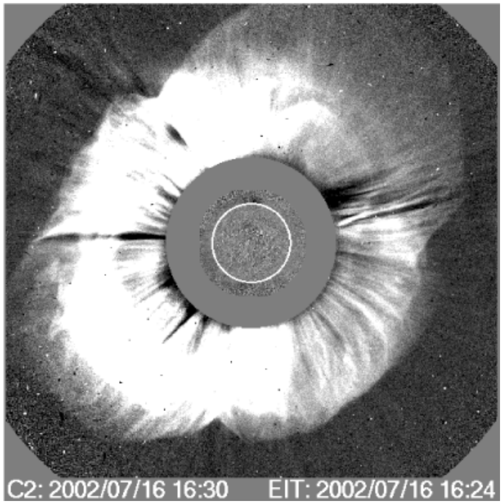
Halo CMEs



Front-side halo



back-side halo



- Halos known for a long time (Howard et al 1982, but routinely observed only by SOHO
- Front-sided halos are likely to impact Earth
- The high kinetic energy of the halos allows them to travel far into the interplanetary medium and impact on Earth causing geomagnetic storms.

- Halos are >2 times faster on the average
- Halos are associated with bigger flares

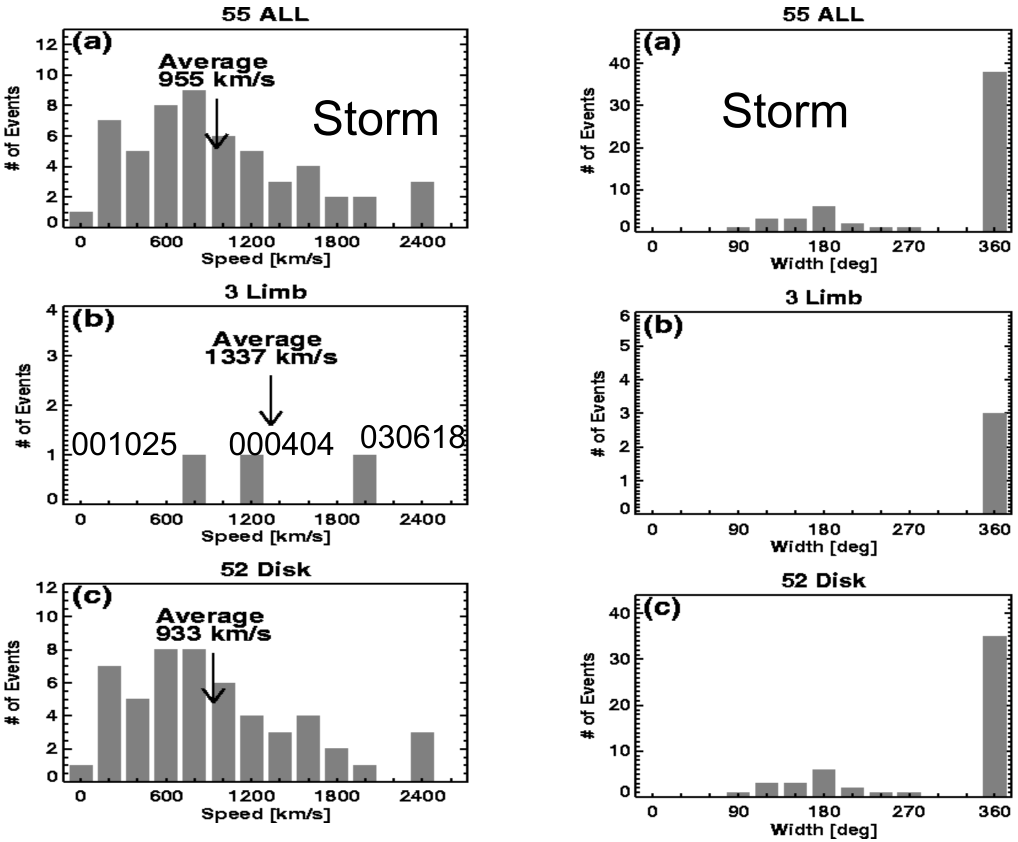
Geoeffective CMEs

59 strong (Dst ≤-100 nT) storms (1996-2003) were analyzed (Gopalswamy, 2006)

- 55 were CME-associated
- 3 were probably CIR-related
- 1 probably CIR

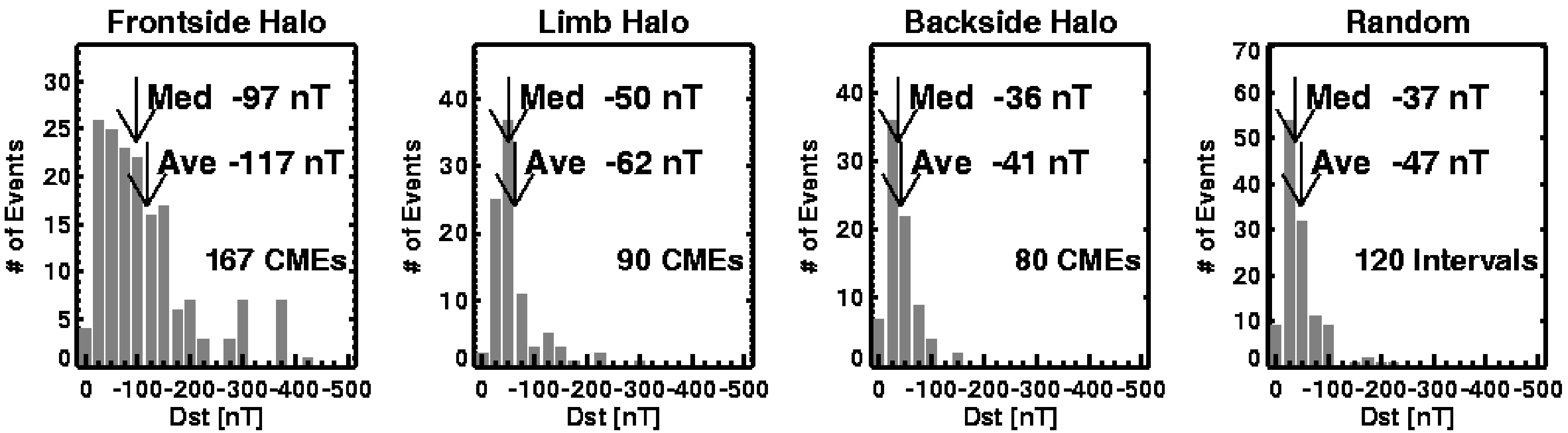
Geoeffective CMEs are faster and wider on the average.

Mostly full halos (69%) and partial halos (31%)



Geoeffectiveness of Halos

378 halos of cycle 23 analyzed for Geoeffectiveness (Dst < -40 nT)



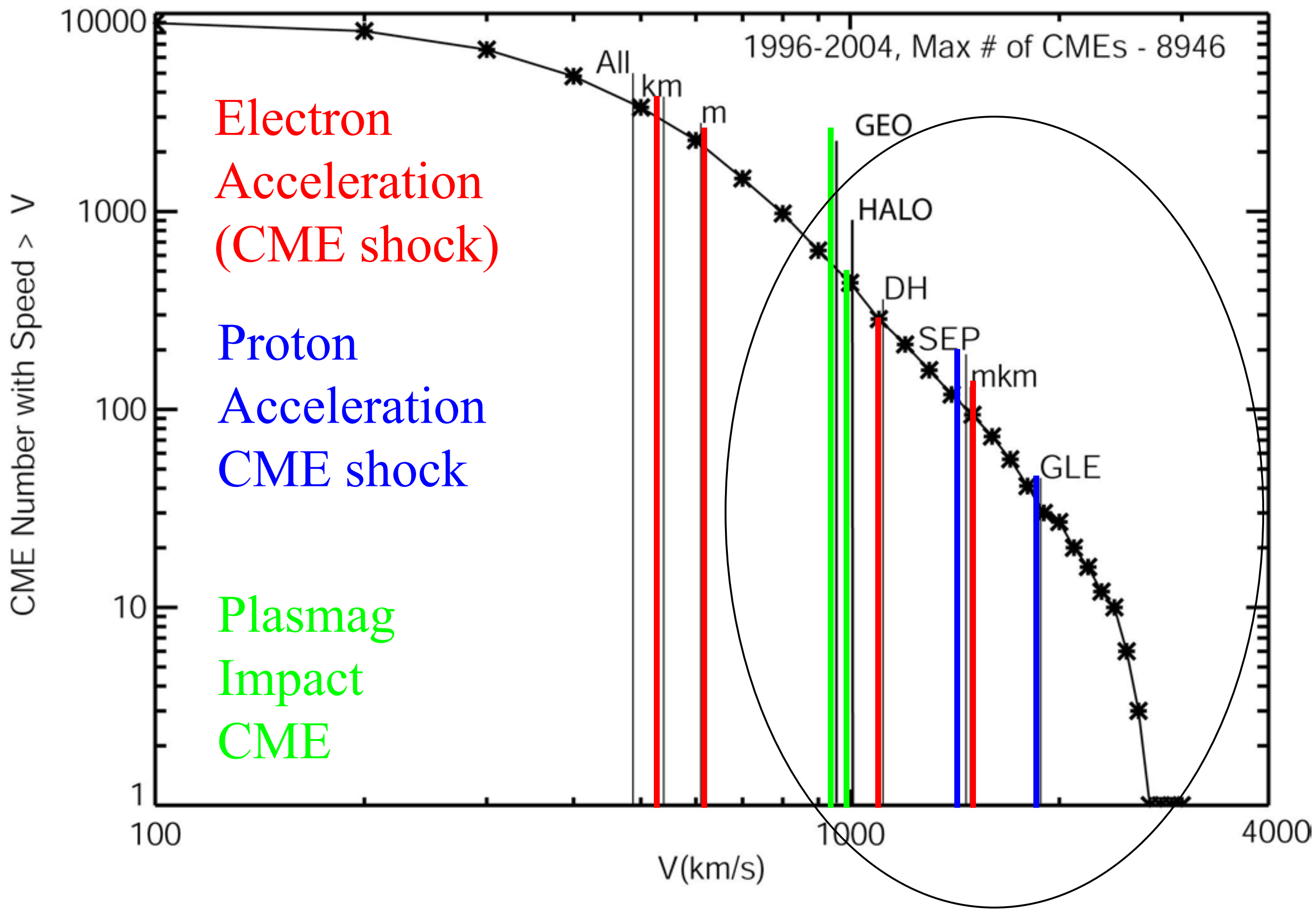
- Source longitude $\Lambda < 45$ deg
- Highly geoeffective

- Source lon
  $45 < \Lambda \leq 90$ deg
- Moderately geoeffective

- Source lon
  $\Lambda > 90$ deg
- Not geoeffective

- Random Dst values
- Similar to Backside halos

Significant CMEs



CMEs of heliospheric consequences V≥1000 km/s

Summary

- CME rate increases by an order of magnitude from minimum to maximum: solar max rate a factor of 2 higher than pre-SOHO estimates
- The mean CME speed is higher by a factor of 2 during solar maximum (this was not established before SOGO era).
- ~10% CMEs important for heliospheric impact
- Only 1-2% of CMEs are important for SEPs
- Halo CMEs are faster than average (and wider); 3%
- Geoeffective CMEs form a subset of front-side halos
- Direct CME impact is essential for geoeffectiveness
- Source location and speed differ for Geo- and SEPeffective CMEs
- Poor correlation between CME rate and SSN is due to high-latitude CMEs
- Polarity Reversal coincides with the cessation of high-latitude CMEs
- High-latitude CME rate has a better (anti)correlation with GCR intensity during A>0 cycle than with the low-latitude rate.
- The opposite is true for the A<0 cycle

Summary

SOHO has observed CMEs almost over a solar cycle, yielding an extensive and uniform data set for a better understanding the CME phenomenon.

Separating the CME rate into high and low latitude rates helps understand the correlation with sunspot numbers, solar polarity reversal, and galactic cosmic ray modulation

The relation between CMEs and Prominence Eruptions is confirmed and recent doubts have been clarified

The combination of SOHO and wind/WAVES data has helped observe direct CME interactions and study their implications for radio bursts and SEP events.

The coupling between CMEs and the solar wind has been possible by combining SOHO data with in situ data resulting in models for estimating the arrival times of CMEs and shocks.

A hierarchical relationship between CMEs and type II bursts has been found, confirming that the most energetic CMEs produce type II bursts over the longest wavelength range and responsible for the large SEP events

Tylka jan 20 05

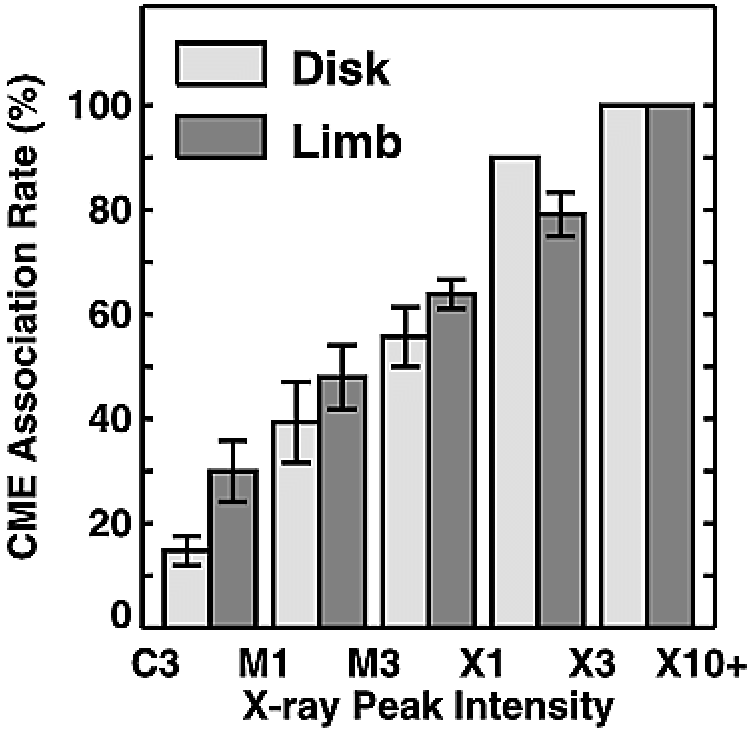
- GLE onset 6:48:40 +/-10s (NM)
- E-folding rise 25 s
- CRNE on IMP8: 06:51:48, probably 06:50
- Electron onset at 6:50:12 +/- 5 s
- 3DP: 6:49 electrons
- For all GLEs, typical delay of e is < 2 min
- Cliver et al. (1982) found 5 min delay, may be an artifact of limited sensitivity

SOHO and Pre-SOHO CMEs

Coronagraph Epoch →	OSO-7 1971	Skylab 1973-74	Solwind 1979-85	SMM 1980,84-89	LASCO 1996-2005
FOV(Ro)	2.5-10	1.5 - 6	3 - 10	1.6 -6	1.2-32
#CMEs	27	115	1607	1206	10500
Mean V (km/s)	---	470	460	350	482
Mean W (deg.)	---	42	43	47	45
Mass (10^{15} g)	---	6.2	4.1	3.3	0.4
Reference	1	2	3	4	5

1 Tousey (1973)
2 MacQueen et al 1974
3 Michels et al 1980
4 Brueckner et al., 1995; Gopalswamy 2004

CME-Flare Association



Yashiro et al. 2005 JGR

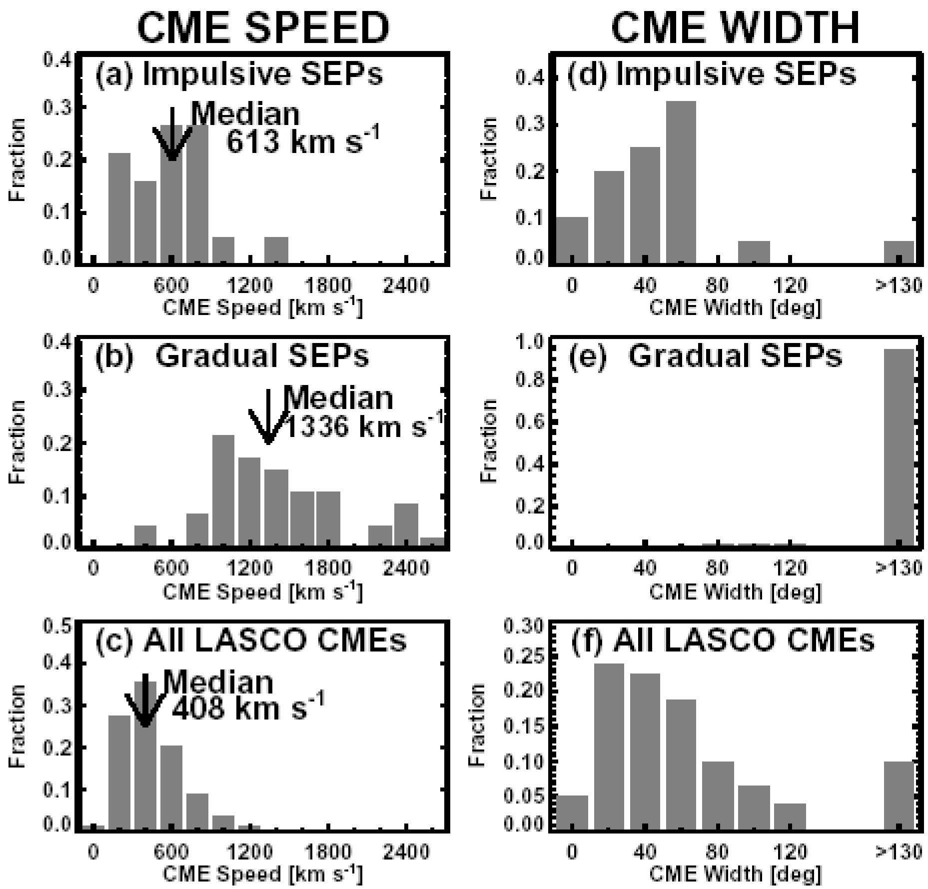
- The CME association rate clearly increases with
- (1) Flare size (20% for C-class, 49% for M-class and 92% for X-class)
- (2) Longitude of the solar source

- The center-to-limb variation of CME association
- Rate is important only for weak flares
- There are some X-class flares (8%) with no CME association.
- ~20% of CMEs may not have been detected by LASCO

Flare size	0-30 deg	30-60 deg	60-90 deg
X	100	100	100
M	84	100	100
C	50	67	100

Estimated CME Visibility function assuming that all limb CMEs are detected by LASCO

Impulsive SEP Events and CMEs



Yashiro et al. 2004

Impulsive SEP events were thought to be Not associated with CMEs.

Recent study using SOHO data shows that ~40% of the impulsive SEP events are associated with CMEs

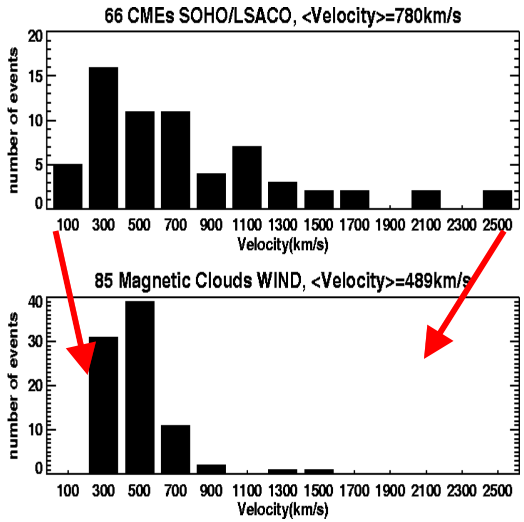
However, the type II burst association is rather poor (~13%)

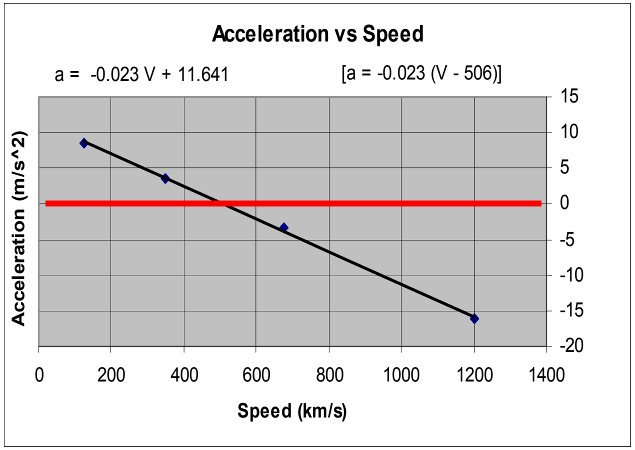
CMEs associated with impulsive SEP events are slightly faster on the average, but the widths are similar to the general population.

Study based on a small sample (38 events). Needs further investigation

Acceleration

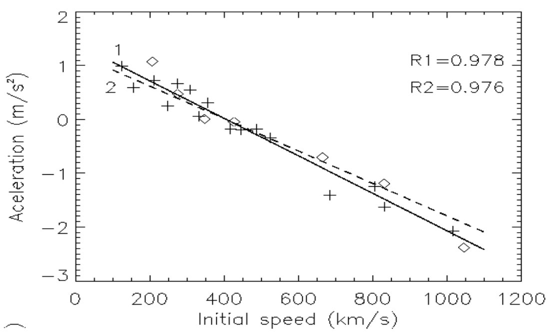
Comparing the speeds of CMEs near the Sun and ICMEs (magnetic clouds) at 1 AU





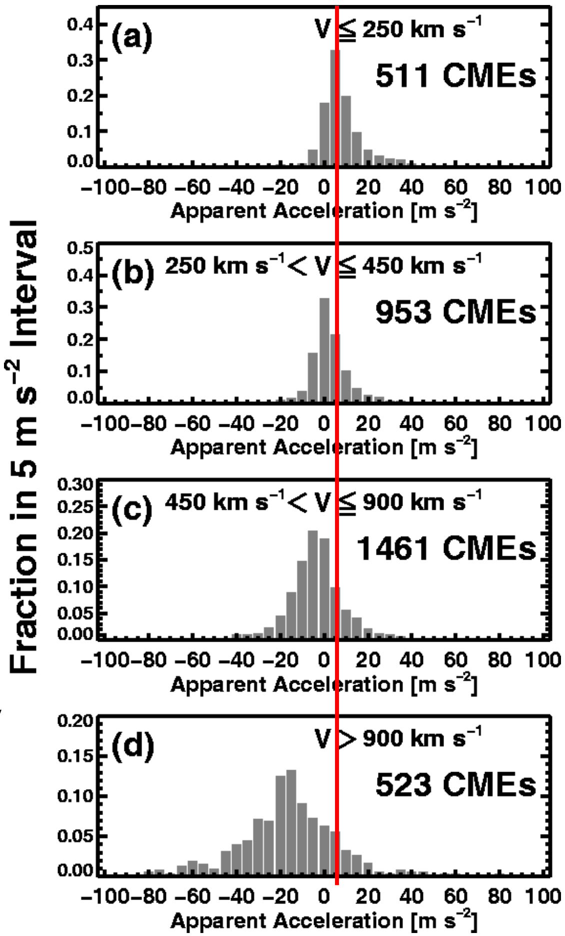
$$a = -0.023\,(V - 506)$$

Gopalswamy et al.2000; 2001
Yashiro et al., 2004,
Gopalswamy, 2004

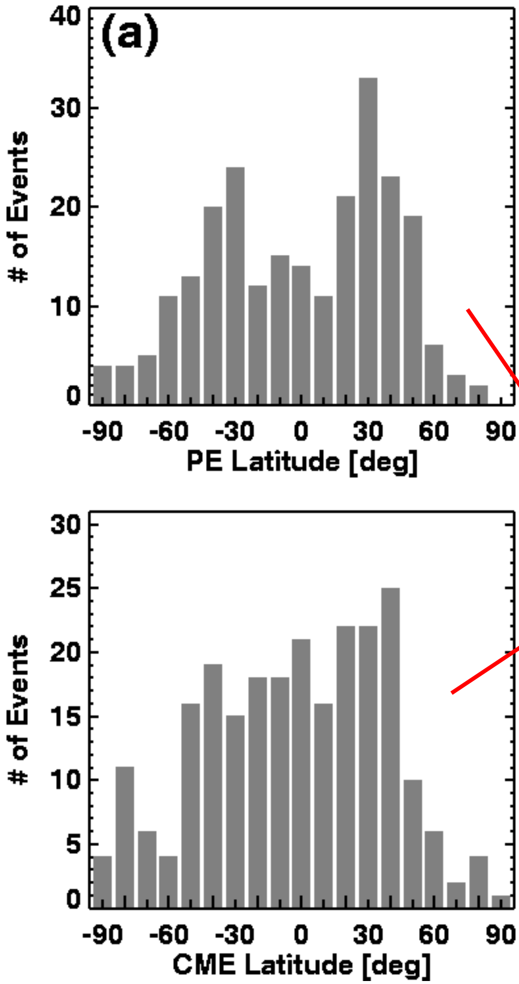


a = - 0.0054 V + 2.193
a = - 0.0054 (V – 406)
a =0 for V=406 → CMEs riding on the solar wind

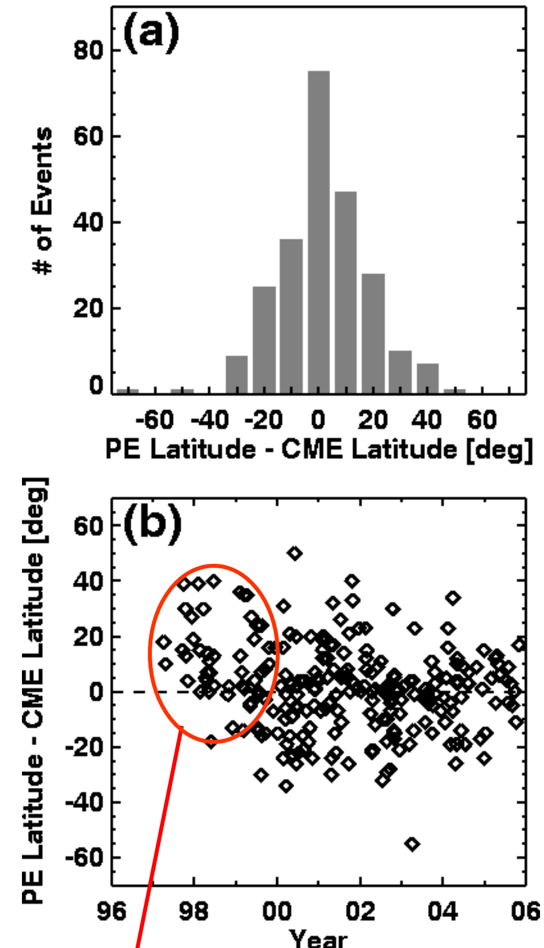
- The dependence of acceleration a on speed V is similar in the LASCO FOV and over the Sun-Earth distance
- Very slow CMEs accelerate
- Very fast CMEs decelerate
- CMEs near slow wind speed show little acceleration
- Near the Sun, a has propelling, gravity & drag components



CMEs and Prominence Eruptions



- Prominence eruptions from Nobeyama radioheliograph and SOHO CMEs confirmed the high-degree (83%) of association between CMEs and (PEs)
- CMEless PEs were much slower (20 km/s), attained very low heights and mostly moving horizontally.
- North-south asymmetry in CME and PE rate
- The latitude distributions of CMEs & PEs were different because of non-radial motion of CMEs during solar minimum

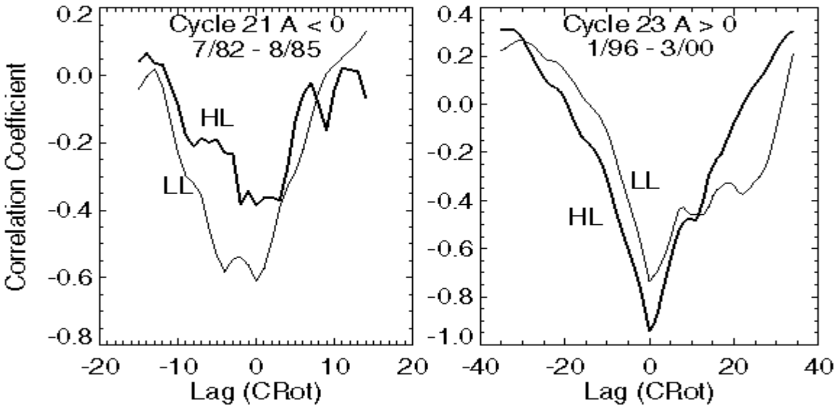


PE latitudes are closer to the poles than CME latitudes during solar minimum

Gopalswamy et al. 2003 ApJ

CMEs & Cosmic Ray Modulation

An interesting consequence of the HL CME rate and polarity reversal is the connection to the modulation of galactic cosmic rays (GCRs). Newkirk et al. (1981) had identified CMEs as the solar origin of the low-frequency power in the interplanetary magnetic field fluctuations and suggested that the solar-cycle dependent modulation of GCRs can be explained by the presence of the fluctuations in the heliosphere. For effective modulation, a higher and more cycle-dependent CME occurrence rate (varying by factors up to 10) was required than pre-SOHO data indicated (Wagner, 1984). SOHO has demonstrated the higher and more cycle-dependent rate (when HL CMEs are considered), and hence the GCR modulation should be possible.



Cross-correlation between GCR intensity and high-latitude (HL) and low-latitude (LL) CME rates for (left) the A< 0 epoch of cycle 21 and (right) the A>0 epoch of cycle 23. Note the switching of the dominant correlation between cycles 22 (A<0) and 23 (A>0).

Gopalswamy, 2004